The James Webb Space Telescope (JWST):
Hubble's Scientific and Technological Successor

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ABSTRACT

The James Webb Space Telescope — the 21st century follow-on to NASA's highly successful Hubble Space Telescope — has moved one step closer to becoming a reality. In addition to selecting the instrument and science teams, NASA will soon announce which contractor team — Lockheed Martin Space Systems or TRW Space and Electronics — has won the prime contract to build the high-profile observatory. Now that the agency has proven JWST's feasibility, it will be up to these teams to finalize designs and begin laying the groundwork for assembling one of the largest single-aperture telescopes ever flown. This article provides a general overview of the JWST mission — a centerpiece of NASA's Origins Program — and describes some of the technological challenges that the NASA team faces.

Mission in Brief

Primary Mirror
6-Meter Class Segmented Active Optic

Wavelength Range
0.6 to 28 µm

Instruments
Near-Infrared Multi-Object Spectrometer
Near-Infrared Camera
Mid-Infrared Camera/Spectrometer

Payload Mass
About 12,000 lbs. (5,400 kg)

Launch Vehicle
Expendable Launch Vehicle

Orbit
Lagrange Point 2 (1.5-million km or 940,000 miles from Earth)

Mission Length
5 years (10 year goal)

1. THE LOGICAL FOLLOW-ON MISSION

In 2010, after 20 years in orbit, NASA will end the Hubble Space Telescope mission. This does not end an era of astronomical discovery; it merely extends it. The same year, the agency plans to launch JWST, which in many ways is Hubble's scientific and technological successor.

Equipped with a large, 6-meter-class deployable mirror and a suite of revolutionary, infrared-sensing cameras and spectrometers, JWST will allow us to see even farther into space than is currently possible with Hubble and help us analyze the miniscule specks of light that Hubble cannot even detect. These nascent stars and galaxies are so distant that by the time their light reaches us, it has stretched into the longer, redder wavelength bands and is invisible to the human eye.

Consequently, no one has ever observed this cosmic “dark zone” before because they did not have the tools to do so. But with this “first light machine,” we will finally see what the universe looked like when it was merely a fraction of its current age and size, when the first stars and galaxies were just beginning to take form. In addition to conducting this unprecedented science, JWST will demonstrate revolutionary new technologies needed for future Origins missions. For this reason, the National Academy of Science has ranked JWST as one of NASA’s top science goals for this decade.

2. ADDITIONAL SCIENTIFIC GOALS

In addition to observing these young galaxies, JWST will tackle four other major objectives over the course of its 5-10 year lifetime. It will help determine the geometry of the universe, its age and determine its ultimate fate. Three years ago, two teams of astronomers rocked the scientific world by finding evidence that the expansion of the universe is accelerating rather than slowing down because of the gravitational attraction between the matter within it. Their observations seemed to confirm the existence of a new form of energy that causes the expansion of the universe to accelerate. JWST is capable of studying this phenomenon.

Although mission planners designed the spacecraft primarily to peer to the farthest reaches of the universe, it also can look closer to home. With JWST, scientists can study the history of the Milky Way and its nearby neighbors by studying the old stars and star remnants that formed over the galaxy’s lifetime. Astronomers also will use JWST to study star birth and formation. Its infrared sensors can pierce the dust and gas that surround stellar nurseries and reveal the processes that dictate the mass and composition of stars, as well as the production of heavy elements. And last, NASA designed JWST to study the origin and evolution of planetary systems like our own. JWST may be able to directly detect large, Jupiter-sized planets around nearby stars. Although we cannot image smaller planets directly, JWST’s high resolution will make it possible to see how they behave as a planetary system, especially when they are in the process of formation, which will give us a larger picture of their evolution.

JWST’s Five Scientific Themes

- **Cosmology and the Structure of the Universe**
- **Origin and Evolution of Galaxies**
- **History of the Milky Way and its Neighbors**
- **Birth and Formation of Stars**
- **Origin and Evolution of Planetary Systems**

3. A DIFFERENT WAY OF DOING BUSINESS

As evidenced by its five-part scientific program, JWST is an ambitious mission. A thousand times more sensitive in the infrared than Hubble, JWST will accomplish far more than what current ground- and space-based observatories can do. Yet, JWST will accomplish these scientific feats at just a fraction of Hubble’s size and overall cost. JWST will weigh about 5,000 kg, compared with Hubble’s 11,000 kg, and a medium-sized rocket, not the Space Shuttle, will likely launch the spacecraft. These criteria were aimed at one thing driving down the cost to build a major space-based observatory.

NASA could not have considered a mission of this magnitude just a few years ago. Since NASA began studying the mission in 1995, the agency has made significant progress advancing technologies and management approaches that would allow it to pack a lot of scientific capability into a relatively small package.

4. ORBITAL CONSIDERATIONS

JWST's orbit at the second Lagrange Point (L2), located 1.5-million km (940,000 miles) from the Earth in the anti-Sun direction is allows NASA to perform this mission. The L2 orbit offers a thermally stable environment. At the L2 point, the JWST will be in orbit around the Sun rather than the Earth, as with HST. This arrangement will allow JWST to live in the shadow of a giant sunshade, which will deploy on orbit. In this shadow, the JWST can passively cool to about 35 Kelvin (about 400° below zero Fahrenheit). Although passive cooling represents an old concept, NASA has never flown a mission before that uses this method to reach these extreme temperatures.


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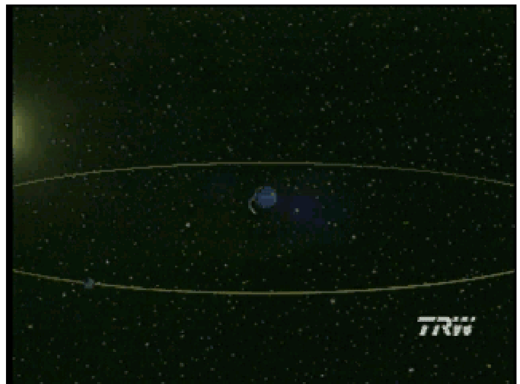

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Fig. 1: JWST Orbit

5. CRYOGENIC COOLING

To observe the farthest reaches of the universe, temperature is an essential consideration. We cannot observe in the near- and mid-infrared wavelength bands (0.6 -0.9 microns is the visible to 28 microns) at temperatures above 35 Kelvin. Anything warmer would create too much of its own infrared "noise" or heat and interfere with JWST's attempt to detect extremely faint infrared photons.

Although NASA could maintain these "cryogenic" temperatures at a different orbital location closer to home, it would come at a cost. The spacecraft would have to carry heavy cooling systems, preventing it from being launched on an expendable launch vehicle and further eroding its science capability since less mass can be allocated to the telescope and instruments. To further reduce heat and stray light, JWST will carry a lightweight sunshield that will deploy to the size of tennis court once the optics are deployed.

Technological Challenges At-A-Glance

1. Developing a lightweight, 6-meter-class deployable mirror that will unfold en-route to its Lagrange Point 2 orbit.
2. Tennis court-sized deployable sunshield, which passively cools instruments and other mechanisms to 35 Kelvin and prevents the electronics from radiating heat and interfering with the collection of extremely faint infrared photons.
3. Constructing a highly capable spacecraft that weighs about 5000 kg.
4. Building low-noise, large-area detectors.
5. Designing, launching and operating JWST at a significantly lower cost than that of its predecessors.

6. COLD MIRRORS AND MOTORS

Even more technologically demanding than the deployable sunshield is JWST's segmented, 6-meter-class lightweight, deployable mirror, which will do what no other mirror has done — it will use a combination of small, ultra-precise actuators and sophisticated computer algorithms to align and property figure the mirror. Developing such a technology is no small task — especially considering the added challenge of making JWST's primary mirror with six times the collecting area of Hubble's, yet more than a factor of 100 lower areal density (kg/m^2) per square meter. In contrast, Hubble's 2.4-meter primary mirror weighs 180 kg per square meter and came in a single piece of polished glass. Although the segmented approach using lightweight materials accomplishes these objectives and allows the telescope to fit inside a commercial rocket fairing, it complicates the task of making sure the mirror holds its proper shape.

Therefore, designers must create a method for measuring errors in JWST's optical system and then correcting the problem while the spacecraft is on orbit. The Hubble's well-known spherical aberration has given the scientific community a great deal of experience in this arena.

Once in orbit, JWST will take several images of stars. With those images, ground controllers will use sophisticated computer algorithms to determine the level of distortion in the mirror segments caused by the super-cold temperatures of space, misalignment and fabrication errors. Unlike any other mirror system, ground controllers can correct distortions by activating computer-controlled mechanical actuators that move and deform the mirror segments until they are perfectly aligned and shaped. Their goal is to reduce the size of these distortions to no more than 0.5 microns, 200 times smaller than the width of a human hair. These actuators need to work in extremely cold temperatures, which adds another level of complexity to the task. This on-orbit wavefront sensing control now under study at the Jet Propulsion Laboratory will undoubtedly find applications in other NASA and Defense Department missions.

6.1 Advanced Mirror System Demonstrator (AMSD)

To foster the development these technologies, NASA, the Air Force and the National Reconnaissance Office created the $30 million Advanced Mirror System Demonstrator (AMSD) program and awarded contracts to three companies to build three 1.6-meter versions and to test them in vacuum chambers. The prime contractor, with NASA's concurrence, will decide next year which technology ultimately will fly.

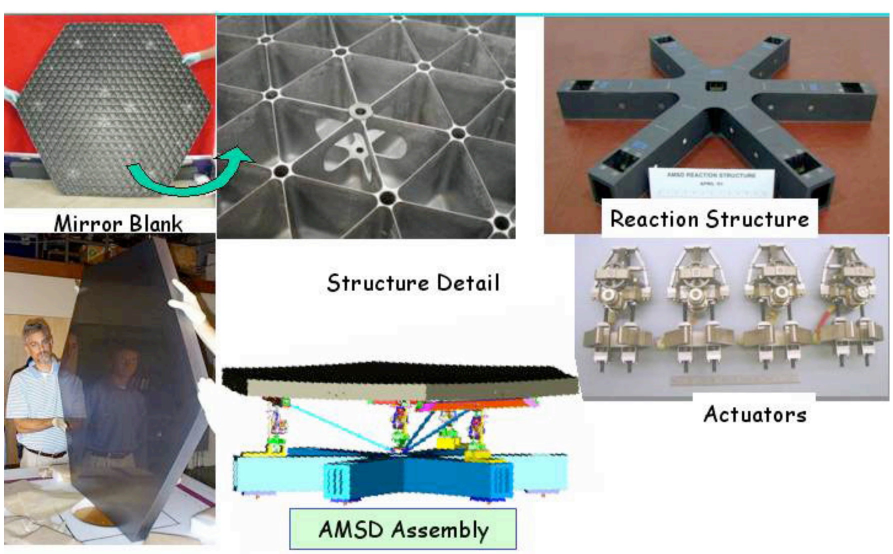

Fig. 2: Ball AMSD Hardware

At this point, however, the contest is still very much alive. Ball Aerospace of Boulder, Colorado, is investigating a semi-rigid design made of beryllium. With its four actuators, this mirror design requires the least amount of on-orbit correction. However, a beryllium mirror will fly on the Space Infrared Telescope Facility (SIRTF), and therefore, NASA has experience with the technology.

Goodrich, of Danbury, Connecticut, is developing a more complex design, which features fused silica that measures just a few millimeters thick, much like a piece of cellophane. Equipped with 37 actuators, the AMSD model offers the greatest amount of figure correction.

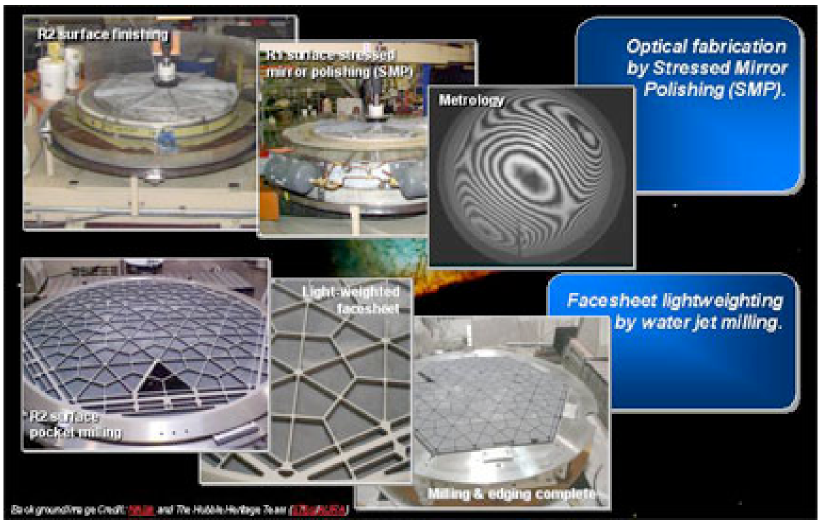

Fig. 3: Goodrich AMSD Hardware

Kodak, of Rochester, New York, is building a model that falls somewhere between the other two in terms of complexity. Made of glass, this concept has 16 actuators.

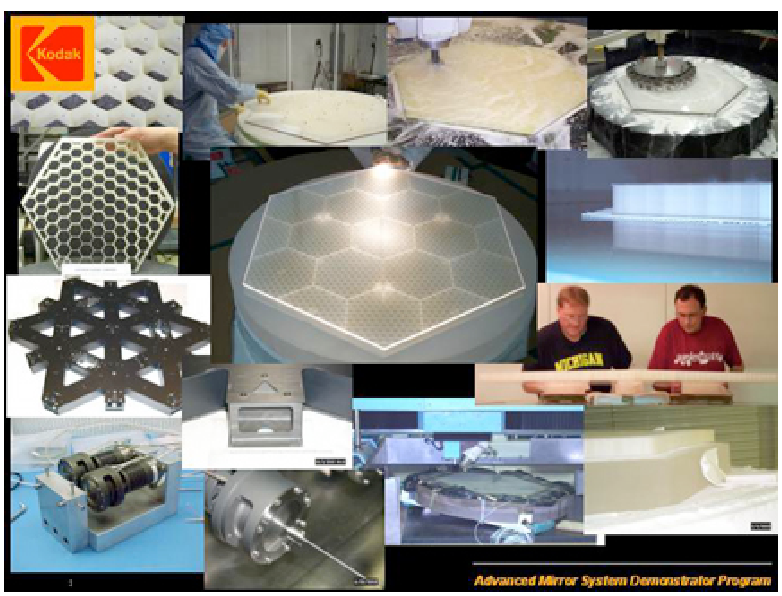

Fig. 4: Kodak AMSD Hardware

7. INTEGRATED SCIENCE INSTRUMENT MODULE

The telescope will carry three instruments. The Near-Infrared Camera (NIRCam), provided by a team led by the University of Arizona, will be JWST's primary imager in the wavelength range of 0.6 to 5 microns. Required by many of the core science goals, the instrument is particularly well suited for detecting the first light-emitting objects that formed after the Big Bang. It also will come equipped with a coronagraph, which scientists will use to obtain images of debris disks, like our own Kuiper Belt, and massive giant planets around nearby stars. With the camera's tunable filter, astronomers can change the filter of the camera to any narrow color range, which will allow them to isolate objects with special color features, particularly in the very distant universe.

A multi-object Near-Infrared Spectrometer (NIRSpec), provided by the European Space Agency, will serve as the principal spectrograph in the 0.6- to 5-micron wavelength range. Spectroscopy is the study of light after it has been separated into its component colors. This diagnostic tool reveals the composition, temperature and other physical characteristics of celestial objects. Its ability to obtain simultaneous spectra of more than 100 objects in a 9-square arc-minute field of view particularly interests the scientific community. By obtaining data on many objects in one observation, astronomers can better characterize the early universe and increase their chances to find rare and unique objects through a factor of 1000 increase in observing efficiency.

And the Mid-Infrared Instrument, provided by an international collaboration led by the Jet Propulsion Laboratory, will provide imaging and spectroscopy at wavelengths of 5 to 28 microns. This capability opens a new window of discovery for scientists. This instrument will study the creation of the first heavy elements and the formation and evolution of galaxies and very old stellar populations. It is uniquely capable of studying the very early stages of star and planet formation, in regions where all visible light is blocked by dust and most of the emission is radiated at mid-infrared wavelengths.

All three instruments are packed into a special module that will form the heart of JWST. The so-called Integrated Science Instrument Module (ISIM) provides the structure, thermal environment, control electronics and data handling for the science instruments and the Canadian Space Agency- provided fine-guidance sensor.

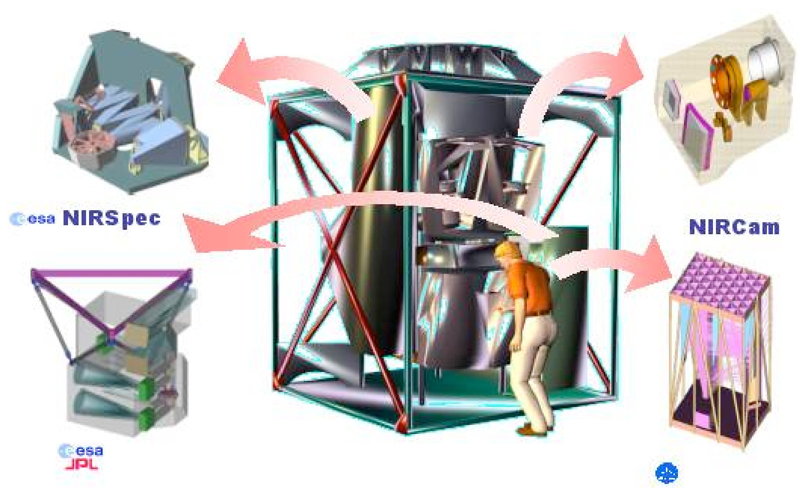

Fig. 5: ISIM Instruments

However, it must do this by maintaining two very different temperature regimes. The optics and instruments must operate at a chilly 35 Kelvin, while the electronic computer systems prefer much warmer temperatures of about 250 Kelvin. A dewar filled with solid hydrogen or a mechanical cryo-cooler will provide additional cooling for the mid-infrared detectors, which work best at about 7 Kelvin.

JWST’s ISIM features two groundbreaking technologies — large-format detectors for all three instruments and a programmable spectrometer aperture mask (microshutters) for the Near-Infrared Spectrometer. They are vital for carrying out the telescope’s rigorous scientific program.

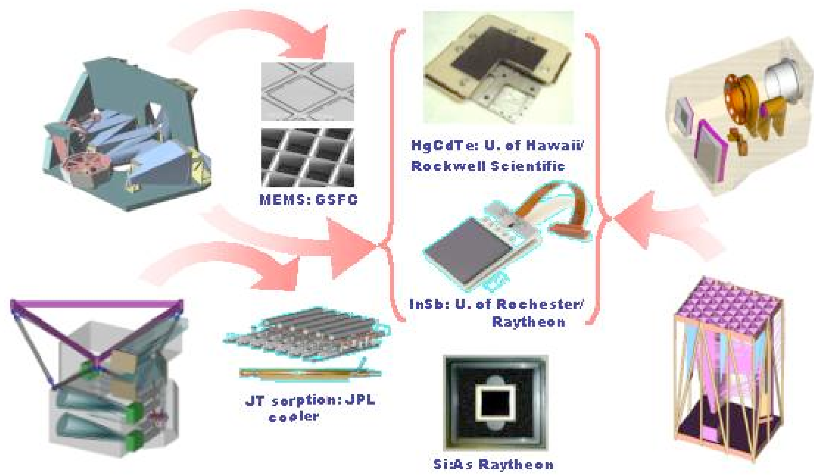

Fig. 6: Detector Technology

8. DETECTORS

The detector is the heart of any astronomical instrument. It records the position, intensity and, by means of filters and spectrographs, the wavelength of incoming radiation. Because JWST’s prime targets are intrinsically faint, with as few as a single photon arriving every second, its detectors must be more sensitive than any detector ever flown. Furthermore, because the detectable first star-forming regions in the universe are very rare, JWST must be able to image large areas of the sky and JWST’s detector assemblies must be large mosaic arrangements of 4 million pixel arrays for a total of 64 million pixels. This detector complement is nearly 500 times larger than that employed by NASA’s Space Infrared Telescope Facility, which is scheduled for launch during 2003.

Indium antimonide (InSb) and mercury-cadmium-telluride (HgCdTe) make the best near-infrared detectors. Researchers have used both types of materials to develop 2,000 x 2,000 (2k x 2k) detector arrays, which contain 4 million pixels and are about 10 times larger than a standard-sized television screen. However, they have yet to develop anything approaching the size needed by JWST because the underlying electronics make larger devices difficult to build. Through JWST’S technology-development program, though, researchers believe they can accomplish their goal by placing close-to-perfect 2,000 x 2,000-pixel chips into a mosaic assembly to achieve the needed size.

Currently, Rockwell Scientific is developing a prototype array using HgCdTe and Raytheon is pursuing one made of InSb. NASA has funded three different laboratories to develop and assess their quality. Once they complete their tests, NASA will choose by mid-2003 which version to fly. The winners must ship flight-ready arrays to instrument makers by 2006.

For the mid-infrared instrument, NASA has decided to use a detector made of arsenic-doped silicon (Si:As) because it works well in this wavelength band. Keeping these detectors even cooler than the spacecraft itself represents a significant challenge. Therefore, instrument planners must install either a hydrogen cryostat or a cryo-cooler that will chill the detectors to a very cool 7 Kelvin.

9. MICROSHUTTERS

Multi-object spectroscopy using JWST'S Near-Infrared Spectrometer represents another quantum leap in space-based astronomy. To characterize the nature of the early universe, JWST will have to take spectral data of many different targets simultaneously. On the ground, this is relatively easy. From camera images, astronomers simply choose the objects they wish to target in their spectral studies and they create an aperture plate that allows light only from those targets to enter the spectrometer. The technique is like punching holes in a piece of cardboard.

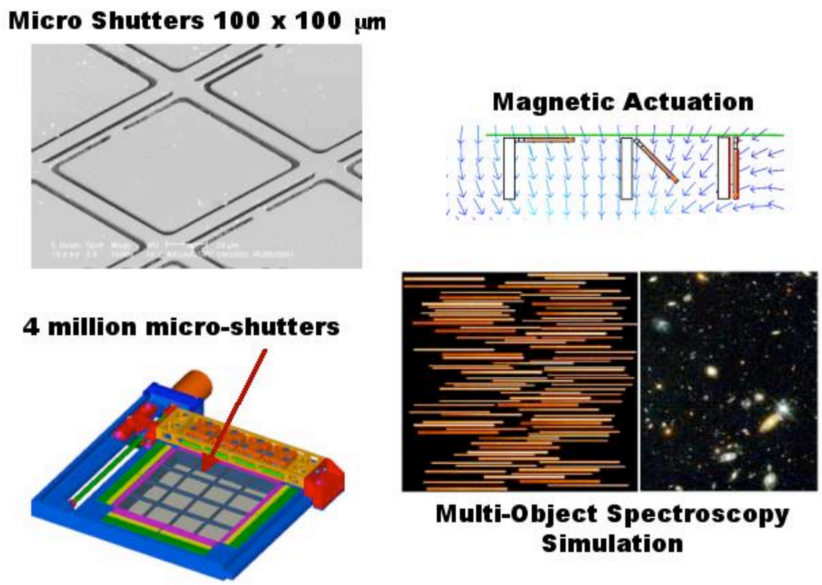

Fig. 7: Microshutter Technology

Creating aperture plates for space-based observatories cannot be done on the ground. However, engineers believe that the Micro-Electro-Mechanical Systems (MEMS) technology offers a revolutionary solution. The Goddard Space Flight Center currently is developing NASA's first-ever MEMS device that instrument makers will install in the European-built Near-Infrared Spectrometer. Featuring 2 to 4 million microscopic shutters aligned on a silicon grid — each no larger than a dust mite — the large-format device will perform like the aperture plate used on ground-based spectrometers.

Instead of punching holes, however, ground controllers will send commands directing specific shutters in the array to open or close, forming "slits," depending on which objects astronomers have identified for study. The shutters open or close through magnetic actuation. The technology will allow astronomers to simultaneously gather spectral data on at least 100 objects per observation.

10. PARADIGM-SHIFTING TECHNOLOGY INSERTION

Through a combination of innovative systems engineering and the infusion of breakthrough technologies, like its active optics and ultra-low noise detector arrays, NASA is succeeding at containing costs. Competition is key to NASA's success. The guiding philosophy — borne out by experience — was to keep the specter of competition alive in the pre-development study timeframe for as long as possible. This approach engendered maximum co-investment by industry and ensured the involvement of the best engineering scientific teams.

11. PARTNERSHIPS

International partnering is one way that NASA also hopes to keep down costs for this order-of-magnitude increase in scientific capability over that of Hubble. The European Space Agency (ESA) is contributing about $200 million (U.S.) for a 15 percent observing share and the Canadian Space Agency (CSA) will contribute more than $50 million for its roughly 5 percent share. Truly an international endeavor, the JWST science teams also include private-sector partners from Canada and Europe.

In addition to its partnerships with Europe and Canada, NASA has relied on the expertise of its field centers, including the Goddard Space Flight Center, Ames Research Center, the Jet Propulsion Laboratory and the Marshall Space Flight Center, and several of the Department of Energy's national laboratories. The Space Telescope Science Institute, the same organization that now operates Hubble, will operate JWST'S Science & Operations Center. Universities and a variety of industry groups scattered across the country also are involved in one form or another with the JWST program.

The Department of Defense (DoD) contributed, too, to the technology development effort. It helped to fund the joint mirror technology-development program that led to the development of three distinctly different designs.

12. CONCLUSION

JWST is vital, affordable and scientifically capable and remains the National Academy of Science's top investment priority for NASA Space Astronomy this decade. It is a model of international cooperation and collaboration and continues to thrive under a philosophy that demands clear, centralized management and strong systems engineering. As of today, the team has proven all major technologies, including the viability of lightweight active optics and image-based wavefront sensing and control. Now, with the selection of a prime contractor, the JWST program officially moves to the next phase of its development, a step closer to launching a new era of astronomical discovery. In the end, JWST will touch the lives of thousands of scientists and engineers from across the United States, Canada and Europe, to say nothing of the astronomers worldwide, whose discoveries may well change the way we see ourselves and our place in the universe.

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